Electronic Version
Stylesheet Version v1.1.1

Description

VEHICLE AND NONLINEAR CONTROL METHOD FOR VEHICLE

BACKGROUND OF INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to a vehicle and a nonlinear control method for a vehicle.

[0003] 2. Background Art

[0004] The operation of a vehicle can include controlling any of a number of systems within the vehicle. For example, the speed of a vehicle may be controlled by controlling the torque output of the engine or other torque producing devices. Further, a spark-ignition (SI) engine that is equipped with electronic throttle control (ETC) has three actuators capable of modifying torque independently of driver input. These modifiers are the throttle angle, the fueling rate, and the spark timing. The engine torque response to throttle angle change may be relatively slow

compared to the other two methods, mainly due to the dampening effect of the intake manifold volume.

[0005] Despite the slow response, changing the throttle angle remains an effective means for controlling the torque production of the engine, because it has a wide range of authority and does not compromise the efficiency of combustion. Conversely, the torque response to changing the fueling rate and the spark timing is much faster; however, neither of these modifiers has the range of authority of changing the throttle angle. Reducing the engine torque by changing the fueling rate in an SI engine has poor resolution. In addition, changing the spark timing can result in a lower combustion efficiency which has an adverse effect on fuel economy.

[0006] The above considerations suggest that in cases where fast response is not a primary concern, the throttle angle is the most suitable lever for engine torque control. Hence, it is the most appropriate and sufficiently fast actuator in the case of vehicle speed related functions. The vehicle speed related functions include such things as a driver initiated acceleration request, a desired speed as set in a cruise control (CC) system, and a vehicle speed limit (VSL) that is a predetermined upper speed limit for vehicle op-

eration. Recognizing that the longitudinal motion of the vehicle is heavily influenced by nonlinear factors--e.g., aerodynamic drag--it is natural to introduce nonlinearity into the control method to address this. In addition, using a nonlinear function to control a relatively slow control lever, such as an engine throttle, can increase the response of the control lever, thereby improving vehicle control.

[0007] One method of controlling the vehicle speed with a cruise control system is described in U.S. Patent No. 5,137,104 issued to Etoh on August 11, 1992. Etoh describes determining a driving force of an engine to maintain a target vehicle speed in accordance with a nonlinear relationship between the target vehicle speed and a target variable. The Etoh method uses a conversion coefficient based on the target vehicle speed, that is chosen from a lookup table. The conversion coefficient is then applied to a vehicle speed error, which is added to a throttle angle error term, which is then applied to a drive circuit to actuate a throttle valve.

[0008] Although the conversion coefficient table is based on a nonlinear relationship between vehicle speed and throttle angle, the equation used by the drive circuit to control the

throttle angle is actually linear. Moreover, the nonlinear relationship used to determine the conversion coefficient is based on a target vehicle speed, not a vehicle speed error which considers the current vehicle speed. In addition, because the conversion coefficient is taken from a table, an elaborate interpolation scheme must be used when the target vehicle speed does not exactly match a table value.

[0009] Therefore, a need exists for a vehicle and a nonlinear control method for a vehicle which improves the response of one or more vehicle system controls.

SUMMARY OF INVENTION

[0010] Accordingly, the present invention provides a vehicle and a nonlinear control method for a vehicle that improves the response of one or more vehicle system controls.

[0011] The invention also provides a nonlinear error-based control for a vehicle that responds more aggressively when a current vehicle parameter value is farther from a target value, and responds less aggressively when the current parameter value is closer to the target value.

[0012] The invention further provides a nonlinear error-based method for controlling a vehicle speed that utilizes a single integrator regardless of which vehicle speed control system is being used, thereby providing an improvement

over other methods which apply an integrator in only one type of vehicle speed control system, or which use separate integrators for different speed control systems, each of which necessitates switching in and out of control modes and resetting the integrator each time the mode is switched.

[0013] The invention also provides a method for controlling a vehicle using a nonlinear error-based control. The method includes determining a current value of a first vehicle parameter, and determining a first error. The first error is the difference between a first target value of the first vehicle parameter and the current value of the first vehicle parameter. A first vehicle request is then determined; the first vehicle request is a nonlinear function of the first error.

[0014] The invention further provides a method for controlling a vehicle using a nonlinear error-based control. The method includes determining a current value of a vehicle parameter, and determining a first error. The first error is the difference between a target value of the parameter and the parameter current value. A first gain is applied to the first error thereby producing a first vehicle request. The first gain is a function of the absolute value of the first error.

[0015] The invention also provides a vehicle including a torque producing device operable to propel the vehicle. At least one sensor is configured to measure a vehicle parameter and to output signals related to the measured parameter. A controller is configured to receive signals from the at least one sensor, determine a first error, and determine a vehicle request, thereby facilitating control of the torque producing device. The first error is a difference between a target value of the vehicle parameter and a measured value of the vehicle parameter. The vehicle request is a nonlinear function of the first error.

BRIEF DESCRIPTION OF DRAWINGS

[0016] Figure 1 is a schematic representation of a vehicle in accordance with the present invention;

[0017] Figure 2 is a control diagram flowchart illustrating a method of the present invention;

[0018] Figures 3A-3C are graphs illustrating a gain used in an equation diagrammed in Figure 2; and

[0019] Figure 4 is a control diagram flowchart illustrating a transfer function used in a method of the present invention.

DETAILED DESCRIPTION

[0020] Figure 1 shows a schematic representation of a vehicle 10 in accordance with the present invention. Although the vehicle 10 is a hybrid electric vehicle (HEV), the invention encompasses other vehicle types, for example, conventional internal combustion engine vehicles, diesel engine vehicles, fuel cell vehicles and hybrid fuel cell vehicles. The vehicle 10 includes an engine 12, a first motor 14, and a second motor 16. The engine 12 and the first motor 14 are connected through a power transfer unit, which in this embodiment is a planetary gear set 18. Of course, other types of power transfer units, including other gear sets and transmissions, may be used to connect the engine 12 to the first motor 14.

[0021] The planetary gear set 18 includes a ring gear 20, a carrier 22, and a sun gear 24. An engine shaft 26 is connected to the carrier 22, while a motor shaft 28 is connected to the sun gear 24. A motor brake 30 is provided for stopping rotation of the motor shaft 28, thereby locking the sun gear 24 in place. Because this configuration allows torque to be transferred from the first motor 14 to the engine 12, a one-way clutch 32 is provided so that the engine shaft 26 rotates in only one direction.

[0022] The ring gear 20 is connected to a shaft 34, which is con-

nected to vehicle drive wheels 36 through a second gear set 38. The second motor 16 is also connected to the wheels 36 through a second motor shaft 40 and the second gear set 38. The motors 14,16, the planetary gear set 18, and the second gear set 38 may generally be referred to as a transaxle 42.

[0023] The first and second motors 14,16 are electrically connected to a battery 44. The battery 44 provides electrical power to one or both of the first and second motors 14,16 when they output mechanical energy to the wheels 36. Alternatively, one or both of the motors 14,16 can act as a generator that can be used to charge the battery 44 when the vehicle is in a regenerative mode or when the engine is running. Moreover, either of the motors 14,16 can act as a generator to provide electrical power to the other motor.

[0024] In this embodiment, a vehicle system controller (VSC) 46 controls the engine 12 and the motors 14,16. Although shown as a single unit, the VSC 46 may be made up of more than one controller. For example, rather than the single VSC 46, the engine 12 and each of the motors 14,16 may have their own control unit in the form of a separate hardware device. Alternatively, the controllers for

the engine 12 and the motors 14,16 may be software controllers that reside within one or more hardware controllers, such as a vehicle system controller. In addition, the VSC 46 may communicate with other high level controllers, such as a brake control module (BCM). A BCM can be integrated into the VSC 46, or it may be a separate hardware device.

[0025] In order to provide information to the VSC 46 about various vehicle conditions, a number of sensors are used to take measurements and provide information to the VSC 46. A first sensor 48 is in communication with the VSC 46, and is configured to measure a parameter of the engine 12, such as the engine speed. A second sensor 50, also in communication with the VSC 46, is configured to measure a parameter of the first motor 14, such as the motor speed, or the current draw. Similarly, a third sensor 52, also in communication with the VSC 46, is configured to measure a parameter of the second motor 16.

[0026] Additional sensors 53, 54,56, similarly communicate with the VSC 46. The sensor 53 is configured to measure the speed of output shaft 57, which allows the speed of the vehicle 10 to be determined. The sensors 54, 56 are configured to measure the speed of the wheels 36; the wheel

speed can be used to complement the measurements of the sensor 53 in determining the vehicle speed. Generally, each of the sensors 48,50,52,53,54,56 is used to measure a vehicle parameter. Of course, the vehicle 10 may be equipped with fewer or more sensors as desired.

[0027] In addition to inputs from the various sensors, the VSC 46 also receives input from an accelerator pedal 58. The accelerator pedal 58 responds to driver demands and provides inputs to the VSC 46 to control one or more of the torque producing devices--i.e., the engine 12 or the first or second motors 14,16. The torque of the engine 12 may be controlled by adjusting the angle of a throttle 60, the fueling rate, the spark timing, or some combination thereof. Although the engine 12 shown in Figure 1 is an internal combustion engine, the engine 12 could be a diesel engine having its torque controlled by controlling the fueling rate and/or injection timing. In addition, as discussed above, the present invention contemplates many different types of vehicles, including fuel cell vehicles. Shown in phantom in Figure 1 is a fuel cell 62 which can be configured to communicate with the VSC 46 and to provide electric power to the battery 44, or either of the motors 14,16.

[0028] The vehicle 10 is configured to use a nonlinear error-based control method in accordance with the present invention. By way of example, the method will be explained in the context of controlling the speed of the vehicle 10 by using a nonlinear speed error function. Of course, the present invention contemplates the use of other nonlinear error-based functions to control a vehicle, such as the vehicle 10. For example, longitudinal motion of a vehicle can be represented equivalently in different physical domains, such as acceleration, torque and force. Therefore, vehicle control can be implemented using a nonlinear control method in any of these domains.

[0029] Turning to Figure 2, a method in accordance with the present invention is illustrated. Initially, the method will be explained in the context of a speed control system, or cruise control system, which may reside within the VSC 46. Alternatively, the cruise control system could be maintained in a separate controller. Block 64 represents a first target value of a first vehicle parameter. In particular, the first vehicle parameter is a vehicle speed, and the first target value is a speed control set point, denoted in Figure 2 as CC desired speed (v_cc).

[0030] A current value of the first vehicle parameter--i.e., the

current vehicle speed--is then determined at block 66. The vehicle speed may be determined from inputs from the wheel speed sensors 50,52, which communicate with the VSC 46. The difference between the first target value and the current value is then determined at summing junction 68. This difference is a first error which will be used to control the speed of the vehicle 10.

[0031] In order to generate a first vehicle request that is a non-linear function of the first error, a first gain (Kcc)--see block 70--is applied to the first error at multiplier block 72. The result of this multiplication is a first vehicle request, which is a speed control system desired acceleration, or CC desired acceleration. The CC desired acceleration is a nonlinear error-based function that can be used to control the vehicle 10. Thus, in one embodiment, the present invention merely creates a nonlinear error-based control function through application of a gain to a determined error.

[0032] To generate a vehicle request that is a nonlinear error-based function, the gain Kcc is itself a function of the speed error (v_cc-v). One example of such a function is illustrated by the following, where Kcc is a function of a proportional gain (K_p) and a variable gain (K_q). The vari-

able gain K_q introduces a nonlinear, quadratic term when it is applied to the determined error. For example, for $K_q = \beta|v\_cc - v|$, the gain Kcc is defined by the following: $Kcc = K_p + \beta|v\_cc - v|$, where Kcc is the first gain, K_p the proportional constant, β is a constant, v_cc is the target speed, and v is the determined current speed. Therefore, when the gain Kcc is multiplied by the speed error (v_cc−v), the resulting control function (CC desired acceleration) is a nonlinear function of the speed error.

[0033] An alternative form of the gain Kcc uses the maximum of the proportional and variable gains, rather than their sum. In particular, the gain Kcc can be defined by the following: $Kcc = \max(K_p, \beta|v\_cc - v|)$, where max is the maximum of K_p and $\beta|v\_cc - v|$. The relationships between the proportional and variable gain terms of Kcc are shown in Figures 3A-3C. For example, Figure 3A shows the proportional gain K_p and the variable gain K_q as separate plots on the graphs. Using either of these two gains alone for the value of Kcc has certain drawbacks. For example, the proportional gain K_p remains constant even as the speed error changes. This means that the same gain would be applied to control the vehicle, regardless of the size of the speed error--i.e., regardless of how far the current vehicle speed

is from the target speed. This can result in a steady state error that keeps the vehicle from reaching the target speed.

[0034] By comparison, the variable gain K_q has an advantage in that it increases as the speed error increases. Thus, control of a vehicle using the variable gain will be more aggressive when the error is larger. Therefore, a control method using this type of gain will reach the target value more quickly than if a proportional gain is used alone. Despite the benefit of using a variable gain such as shown in Figure 3A, a better value for a gain, such as the gain KCC, can be derived by combining the proportional and variable gains. This is because using the variable gain K_q alone, may compromise the stability of a closed loop system, such as a cruise control system, when the speed error approaches zero.

[0035] Figures 3B and 3C show alternative methods of combining the proportional and variable gains K_p, K_q to get a benefit from each type of gain. It is worth noting that the gains shown in Figures 2B and 2C represent only two possibilities for construction of a gain based on an error signal. For example, any positive non-decreasing function of the absolute value of an error can be used to achieve similar

results. Thus, the gains shown in Figures 3B and 3C have the effect of providing a more aggressive control when the error is large and the vehicle is operating away from its target value, and also provides decreased control action when the vehicle is operating close to its set point. Specifically, the overshoot and oscillations caused by the slow dynamics of throttle angle control can be mitigated by using a nonlinear control function as described above.

[0036] Although a method of the present invention can be used to control one aspect of vehicle operation, such as the cruise control, the present invention may also be used to control a number of different vehicle operations, while further employing a nonlinear error-based control method. For example, returning to Figure 2, a second vehicle request (a_dd), or driver desired acceleration, is determined at block 74. As described above with reference to Figure 1, such a request will be received as an input into the VSC 46 from the accelerator pedal 58. As described more fully below, the driver desired acceleration is modified at block 76; however, this modification will not affect the result of the ensuing arbitration at block 78. Therefore, the arbitration at block 78 is assumed to take place between the first vehicle request (CC desired accel-

eration) and the second vehicle request (driver desired acceleration).

[0037] The arbitration that takes place at block 78 results in the determination of a first arbitrated vehicle request. Specifically, the maximum of the first and second vehicle request is determined, resulting in the first arbitrated vehicle request. The first arbitrated vehicle request is itself arbitrated at block 80. The value with which it is arbitrated, is now described.

[0038] As discussed above, control of a vehicle may include a vehicle speed limit, which represents an upper limit beyond which it is undesirable to operate the vehicle. The vehicle speed limit is a predetermined value, and may be programmed into a vehicle system controller, such as the VSC 46. Such a speed limit (v_lim) is illustrated in Figure 2 in block 82. As with the speed control system described above, a method of the present invention can also be applied to the vehicle speed limit, such that a nonlinear error-based vehicle request is generated. Using the nomenclature from above, the vehicle speed limit (v_lim) represents a second target value of the first vehicle parameter (the vehicle speed). As with the CC desired speed above, the vehicle speed limit is combined with the current value

of the vehicle speed, which takes place at summing junction 84. This results in a second speed error (v_lim-v).

[0039] After the second speed error is determined, a second gain (Klim)--see block 86--is applied to the second speed error at multiplier block 88. This results in a third vehicle request (VSL desired acceleration), which may also be a nonlinear error-based function. The particular form of the VSL desired acceleration depends on the second gain (Klim). For example, Klim may have a form similar to KCC, combining both a proportional term as well as a variable term that is a function of the second speed error (v_lim-v). In fact, the present invention may be applied exclusively to the vehicle speed limit rather than also applying it to the CC desired speed and using an arbitration scheme. There are advantages, however, to applying the present invention to more than one control system on a vehicle, and using an arbitration scheme as illustrated in Figure 2.

[0040] One advantage is that the cruise control and the vehicle speed limit control will both benefit from the nonlinear error-based function generated by application of the present invention. Each of these control functions can then be used to improve the response of an otherwise

slow control lever, such as the throttle 60. In addition, by including the arbitration scheme illustrated in Figure 2, a common problem associated with integral controllers is avoided.

[0041] For example, one way to effect vehicle speed limit control is by use of a proportional integral (PI) controller, which regulates the vehicle velocity around the vehicle speed limit. Such a controller includes an explicit integral term in the control equation. The inclusion of an integral term eliminates steady state error. The presence of the explicit integral term, however, makes it necessary to switch in and out of the vehicle speed limit control mode as needed. Each time the control switches to the vehicle speed limit algorithm, the integrator needs to be adjusted to avoid discontinuity in the speed request. As explained below, this problem is eliminated through the use of the present invention, which arbitrates the various vehicle requests prior to the application of an integrator, thereby eliminating the problem of switching in and out of the vehicle speed limit control mode.

[0042] Returning to Figure 2, it is shown that at arbitration block 80, the minimum of the first arbitrated vehicle request and the VSL desired acceleration is determined. This gen-

erates a fourth vehicle request, or a first vehicle acceleration request. Next, a current value of a second vehicle parameter--i.e., the vehicle acceleration--is determined a block 90. Finally, a controller, including a transfer function (G), is applied to the vehicle acceleration and the first vehicle acceleration request at block 92, thereby resulting in a fifth vehicle request, or a second vehicle acceleration request. The controller illustrated in block 92 may be a software controller residing in the VSC 46, or some other controller. Alternatively, the controller at block 92 may be a separate hardware device. The specifics of the transfer function G used at block 92 are described below in conjunction with Figure 4.

[0043] The transfer function G illustrated in Figure 4, is only one example of a transfer function that can be used to generate the second vehicle acceleration request. Moreover, as discussed above, a vehicle, such as the vehicle 10, may be controlled using parameters other than acceleration, for example, torque or force. Each of these three domains are related, and therefore, the present invention can be used to control a vehicle using torque or force requests, rather than acceleration requests.

[0044] Turning to Figure 4, it is shown that the transfer function

G includes a feed forward action, an integration action, and a proportional action. Specifically, the first vehicle acceleration request, shown at block 94, is used directly in the feed forward action, where a gain (Kff)--see block 96--is applied at multiplier block 98. This value is then fed into a summing junction 100, where it is combined with integration and proportional terms. For the transfer function G illustrated in Figure 4, the gain Kff can be any value greater than or equal to zero. For the integration and proportional actions within the controller 92, the difference between the first vehicle acceleration request and the measured vehicle acceleration is determined at summing junction 102. This results in a third error, or an acceleration error, as shown in Figure 4.

[0045] The acceleration error is then used in the remaining two actions within the transfer function. Specifically, a gain (Kp1)--see block 104--is applied at multiplier block 106. The resulting value is then combined with the other terms at summing junction 100. As in the case of the gain Kff, the gain Kp1 may also be any value that is greater than or equal to zero.

[0046] The acceleration error is also used in the integration action. Specifically, a gain Ki--see block 108--is applied to

the acceleration error at multiplier block 110. After application of the gain Ki, the term is then integrated at integrator block 112. The resulting integral action (x_i) is then fed into the summing junction 100, where it is combined with the feed forward term and the proportional term. Unlike the gains Kff and Kp1, the gain Ki is chosen to be a non-zero, positive value. This ensures a continuous updating of the integral term. It should be noted that the integral term also requires anti-windup protection, which is commonly used and applied by those skilled in the art of control systems.

[0047] As shown in Figure 4, the present invention applies an integrator only after each of the various speed controls are arbitrated. This avoids the limitations of other systems discussed above, in which an integrator is only applied to, for example, a vehicle speed limit control. Such a system necessitates switching in and out of the vehicle speed limit control mode, and resetting the vehicle speed limit integrator each time the mode is switched. In contrast, the present invention uses a single integrator for all of the vehicle speed controls, and uses the integrator regardless of which of the vehicle speed controls is the winner of the arbitration. Thus, the integrator is used whether one of

the closed loop requests--i.e., the CC desired acceleration or the VSL desired acceleration--wins the arbitration, or whether the driver desired acceleration--an open loop request--wins the arbitration.

[0048] Because the driver desired acceleration is an open loop request, it is modified at block 76 prior to the arbitration, so the integrator can still be used. Specifically, block 76 represents a second transfer function which is configured to nullify the effect of the integrator shown in Figure 4. Thus, block 76 is labeled "Inv G" to denote a transfer function which is, in general, the inverse of the transfer function G shown in Figure 4. Specifically, when the driver desired acceleration is the winner of the arbitration, and it is desired that the driver desired acceleration pass through the transfer function G unchanged, the proper choice of the gains Kff and Kp1 and the second transfer function InvG can accomplish this. For example, using a transfer function at block 76 that changes the driver desired acceleration from (A_dd) to (A_dd-x_i), and choosing Kff=1 and Kp=0, allows the driver desired acceleration to pass through the transfer function G unchanged. Therefore, in this situation, the second vehicle acceleration will be equal to the driver desired acceleration.

[0049] Although the embodiments described above refer to the control of vehicle speed, and in particular the control of vehicle speed by adjusting the angle of the throttle on an internal combustion engine, the present invention can be used to control a vehicle in different ways. For example, the second vehicle acceleration request shown in Figure 2, which can be used to adjust the angle of the throttle 60 shown in Figure 1, could alternatively be a vehicle request to any of the torque producing devices shown in Figure 1.

[0050] For example, if the engine 12 is a diesel engine, the second vehicle acceleration request may be used by the VSC 46 to control the fueling rate of the engine 12. Where the torque producing device is one of the motors 14,16 the second vehicle acceleration request may be used by the VSC 46 to determine an amount of electricity provided to the motors 14,16 by the fuel cell 62. In addition, as discussed above, the present invention may be used to control a vehicle or any vehicle system for which the use of a nonlinear control is desired.

[0051] While the best mode for carrying out the invention has been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention

as defined by the following claims.